Axial Flow Fan Use At San Manuel Mine

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ABSTRACT

A case study is presented for the use of multiple axial flow main fans as the principle source of the primary mine ventilation system for a large multi level mine. Formerly owned by Magma Copper, BHP Copper Inc.'s San Manuel Mine is a large underground block caving copper mine which started producing copper in 1955. The San Manuel Mine produces over 50,000 tons per day sulfide copper ore. The total airflow into this mine is approximately 800 m^3/s (1,600,000 cfm). Providing adequate ventilation has been a very challenging experience as new, deeper levels are developed. BHP relies on operation of axial flow main fans which offer the flexibility of blade pitch changes to satisfy airflow requirements. The system provides the airflow requirements for development, production, mine dewatering pump stations and underground maintenance shops. The ability to adjust blade pitch manually, provides flexibility and has been a preferred feature to variable speed drives typical of centrifugal fans. In addition, axial flow fans can often be located more conveniently in underground environments where space availability is at a premium. The ventilation practice described in this paper may be useful to other mines with similar layouts.

KEY WORDS

Axial Flow Fan, Blade Pitch, Block Caving, Production Level, Haulage Level, Intake Shaft, and Exhaust Shaft.

INTRODUCTION

The San Manuel Mine is a large multi level block caving operation with a unique ventilation system. The deepest level of the mine lies at 1140 metres (3740 feet) below the surface. Like any other underground operation, having adequate ventilation has been the key to sustain health, safety and productivity of all underground employees. The objective of the ventilation system has been to satisfy air flow quantities above the minimum requirements for a productive working environment in a cost effective manner.

Since 1955 when production began, eight levels of the ore-body have been opened and mined out. Production began at the 1415 level and sulfide ore mining continues at the 2615 to 3570 levels. The pattern of ventilation conceived from the start of the underground mine is still practiced today on the newer levels. In each case the axial flow fan has been the ventilation source of choice rather than the centrifugal fan. These fans in each new fresh air intake level have been installed underground between the fresh air shaft and the ore-body. In order to appreciate why axial flow fans are preferred in some cases, it is necessary to have a brief explanation of how they work.

BRIEF THEORY OF AXIAL FLOW FANS

Axial flow fans are categorized as turbomachines. They have an impeller which is made up of a hub which carry the blades. The impeller is attached to a shaft which is rotated by an electric motor in most common applications. Before and after the blade row it is good practice to install guide vanes or straightener vanes, to reduce swirl and turbulence. The diffuser forms part of the casing that helps in recovering velocity pressure. The rotating impeller causes the blades to increase the air pressure needed for flow. In most applications the speed of the impeller is fixed. The impeller blades are shaped like aerofoils as can be seen in Figure 1.

The fan will generate pressure head H and will cause air quantity Q to flow. The circumferential velocity of the fluid U is at the same speed as the wheel in relative motion and moves along the blade with velocity W

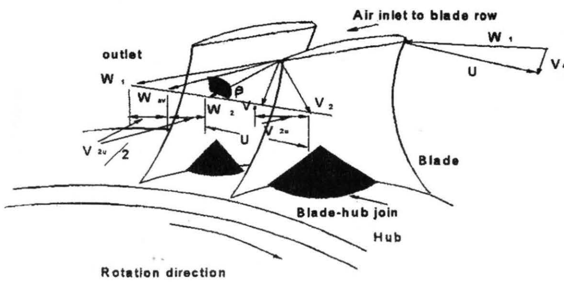

Figure 1. Schematic of a section of an axial flow fan showing the hub, blade row and velocity diagrams.

at an angle β to velocity U. The fluid absolute velocity V is the geometric sum of velocities U and W. Velocity V is projected at an angle α to relative velocity U. The angle α is an absolute velocity angle. The absolute velocity V_{2u} that characterizes flow swirling is the circumferential projection of the absolute velocity and is given by

$$V_{2u} = V\cos\alpha$$
(1)

In a centrifugal turbomachine the head generated is expressed as:

$$H_t = \frac{1}{g}(U_2 V_2 \cos\alpha_2 - U_1 V_1 \cos\alpha_2) \quad (2)$$

Using equation (1), equation (2) becomes:

$$H_t = \frac{1}{g}(U_2 V_{2u} - U_1 V_{1u}) \quad (3)$$

In an axial flow machine the inlet and outlet velocities are the same because the hub radius does not change, i.e. U_2 is equal to U_1. The velocity V_{1u} is assumed to be zero and characterizes flow turbulence at inlet which is assumed to be parallel at entry to the blade row. Equation (3) can now be reduced to

$$H_t = \frac{1}{g}UV_{2u} \quad (4)$$

If the impeller diameter is D and the hub diameter is d_h then the pressure head H_t developed by an axial flow turbomachine or fan in this case can be expressed as a function of flow quantity Q_t:

$$H_t = \frac{1}{g}U^2 - \frac{1}{g}U\frac{\cot\beta}{\frac{\pi}{4}(D^2 - d_h^2)}Q_t \quad (5)$$

In Equation (5), β is the exit incident angle as shown in Figure 1. The pressure generated by a turbomachine is related to the head formula given in equation (5) as:

$$p = \rho g H_t$$
(6)

The airfoil shape of the blade generates higher pressure on the inside (and lower fluid velocity) and lower pressure (and higher velocity) at the back on the diffusion surface. This difference in pressure generates lift forces on the blades. The general theory of airfoils is well covered in many fluid mechanics text books (e.g. White, 1994) The theory of turbomachines, be they fans or compressors is very similar. In fact turbomachine equations for an axial flow compressor are similar to those for a fan (Rogers and Mayhew, 1980).

The design of fans is now very advanced because of the use of computational fluid dynamics (CFD) in turbomachinery. CFD enables the complicated flow in the blade cascade to be simulated and therefore make it possible to design more efficient machines. Stress analysis on the blades can be done using finite element techniques. During design and assembly stages blade tip clearance has to be kept to a minimum, typically 1.5 % of blade length to reduce losses.

Practicing mine ventilation engineers need to know the basics of fan design and selection for the duty to which the machine will be subjected to. Poor choice of fans will result in poor ventilation and often requiring an expensive redesign of the system. In expanding mines fans are normally oversized for future ventilation needs over the years. The only change in this case might be the motor connected to them.

BRIEF DESCRIPTION OF THE OREBODY AND MINING METHOD

The ventilation system at San Manuel Mine, like other mines, was chiefly dictated by the mining method and the extent and geometry of the ore-body. In the block caving system used at San Manuel the ore-body is divided into a grid system of Panels of up to 46 meters (150 feet) or more in width. The panels are then subdivided into blocks of varying sizes. The panels have to be of sufficient size to ensure proper caving action of the ore and the size will vary depending on the nature and extent of the ore-body. Where the ore-body is vertical the height of the slice being mined can be as much as 190 metres (624 ft). Grizzly drifts are driven spaced at 15 metres (50 feet) apart as can be seen in Figure 2.

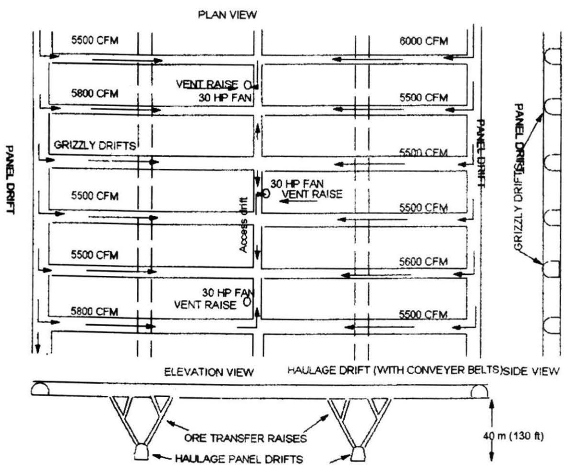

Figure 2. Schematic of panel and grizzly drifts showing ventilation routes, ore transfer and vent fans.

About 7 metres (23 feet) above the grizzly drifts the undercut raises are driven into the ore-body. In the grizzly drifts ore passes, or ore transfer raises, are developed which tie to the haulage level below. When all the transfer raises are developed in a panel block, the ore above is allowed to cave and will flow under gravity into the transfer raise below and fall by gravity to the next level
where it is loaded on haulage trains or conveyer belts. The grizzly drifts are supported to ensure their stability when the ore above them caves in. The grizzly, or production level, is 18.3 metres (60 feet) above the haulage levels in the old levels where trains are used to haul the ore. The new levels which are the 3440 and 3570 levels, are now at 40 metres (130 feet) apart between the production(grizzly) and haulage level, and conveyer belts are now being used instead of muck trains to haul ore.

Ventilation in the production areas has to cover all areas where mining is in progress.

THE ORIGINS OF THE VENTILATION SYSTEM

The San Manuel Mine had three fresh air intake shafts, numbers 1, 2 and 4 with two exhaust shafts 3A and 3B, at the beginning of mining on the 1415 level. Number 2 shaft was used relatively little compared to 1 and 4 shafts. The present ventilation system layout is shown in Figure 3, and it is necessary to give a brief description of the origins of mine ventilation at San Manuel Mine.

Two 200 horsepower, 1.52 meter (5 foot) diameter axial fans, one installed in the ventilation crosscut and the other in the Main Crosscut pulled air from surface at the 1415 level at 1.5 kPa (6.0" w.g.) pressure. When the air traveled to the production areas of the 1415 level through active ore blocks it was then downcast through raises in the inactive blocks to the 1475 Haulage Level. Once at the 1475 level the airflow went through the Hanging Wall Drift and the Main Haulage Loop Drifts to exhaust at Number 3A and 3B shafts. These shafts were also used to hoist ore out of the mine. Approximately 222 m^3/s (471,000 cfm) entered the mine from surface. Of this amount 109 m^3/s (231,000 cfm) was used on the 1415 and 1475 levels. The remainder (113 m^3/s or 240,000 cfm) was used on the 2015 and 2075 levels.

O2015 and 2075 levels number 1 and 4 shaft supplied the air to axial flow fans located on those levels. A 450 hp axial flow fan of 1.83 meters (6 foot) diameter was located at the 2015 level Ventilation Crosscut. The 450 hp fan was adjusted to supply only 44 m^3/s (93,000 cfm) at 1.52 kPa (6.1" w.g.) pressure. A second axial flow fan, a 200 hp of 1.52 m (5 foot) in diameter supplying 25 m^3/s (53,000 cfm) at 1.62 kPa (6.5" w.g.) pressure, was installed at the 2015 Main Crosscut. A third 200 hp axial flow fan was mounted at the 2075 level Main Crosscut and supplied a quantity of 44.4 m^3/s (94,000 cfm) at 1.8 kPa (7.2" w.g.) pressure. Again, like the 1415 level, the 2015 level fresh air was used in the production areas and downcast to the 2075 Haulage Level where it exhausted to the Number 3A and 3B shafts via main haulage drifts.

The fans used at the 1415, 2015 and 2075 level were capable of delivering up to 118 m^3/s (250,000 cfm) at 2.7 kPa (11" w.g.). The motors were chosen to reflect the power needed to move sufficient, amount of air to meet the ventilation needs at that time.

As mining activity expanded more and more levels were added. In the late 1960's and 1970's number 3C and 3D shafts were sunk. These were production shafts which could also be used to exhaust air. Number 5 shaft was also added to be used for services and also as a fresh air intake route.

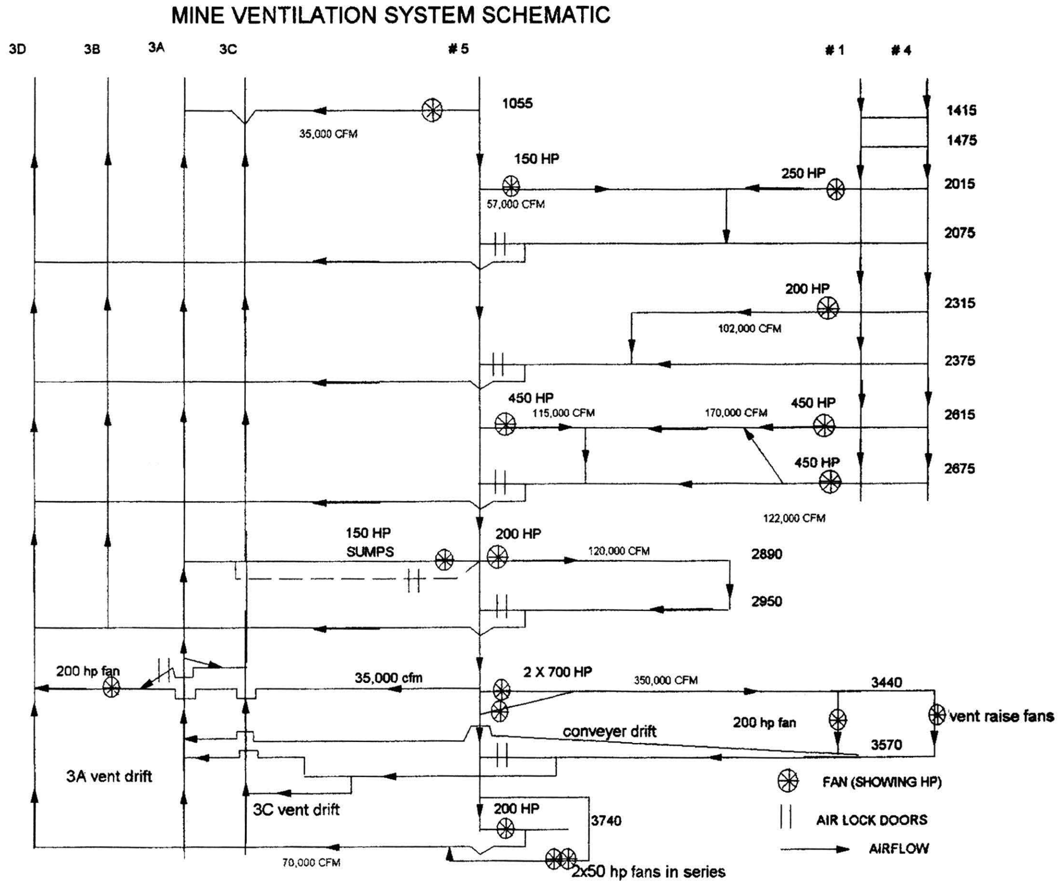

Figure 3. Simplified 2-D schematic of the present ventilation system layout at San Manuel Mine.

DISCUSSION OF THE PRESENT VENTILATION SYSTEM

The ventilation system at San Manuel continued to follow the same basic design and installation philosophy adopted from the foundation of the underground mine starting at the 1415 level. Since the beginning of the mine the following grizzly/haulage levels are now depleted and are now being used for In-situ mining, 1415/1475, 1715/1775, 2015/2075 and 2315/2375. Fans are still operating at the 2015 and 2315 levels as shown on the 2-D ventilation schematic in Figure 3 for In-situ ventilation.

Variable blade pitch axial flow fans are used on all levels of the mine. Axial flow fans are also used in development and production areas, essentially covering all areas of ventilation at San Manuel. The majority of ventilation main fans are installed on the production (grizzly) levels at a distance of approximately 90 to 450 metres (300 to 1500 ft) from the fresh air intake shafts Numbers 1, 4 and 5. Once the air has downcast to the haulage levels it flows to the exhaust shafts Numbers 3A, 3B, 3C and 3D. Numbers 1 and 4 shafts are connected at each level at the main crosscut.

The main fan is located at the main crosscut and will pull air from both shafts into the mine as shown in Figure 5. All fresh air shafts 1, 4 and 5 provide air down to the 2675 level. Number 5 shaft is the only fresh air shaft that can serve the levels lower than the 2675 level but the production and exhaust shafts Number 3A, 3B, 3C and 3D also extend to the deepest levels of the mine.

At the 2615/2675 mining levels, three identical two stage axial flow fans are in use equipped with 450 hp motors. Two fans are located at the main crosscuts of number 1 and 4 shafts at the 2615 and 2675 levels respectively and air flows to the ore-body from the north side. The third fan pulls fresh air from Number 5 shaft, supplying air to the south side of the ore-body. Eventually all the air flow

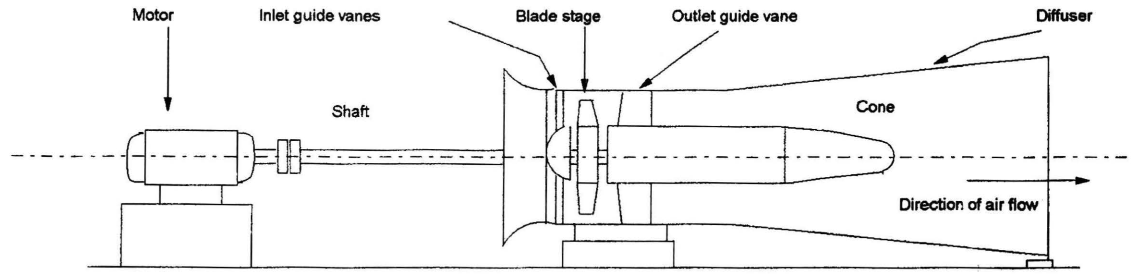

Figure 4. A typical main fan assembly at San Manuel mine.

converges and is downcast to the 2675 level where it exhausts to the production shafts.

Number 5 shafts lies over 1,200 metres (3900 ft) from number 1 and 4 shafts. Number 1 and 4 shafts are spaced at less than 200 metres (656 ft) from each other. The amount of air supplied by all three fans to mining efforts on these levels is approximately 193 m^3/s (410,000 cfm) at a static pressure of 2.5 kPa (10" w.g.) pressure. More than 90 % of the air flow at the 2615/2675 levels is used for production ventilation since very little development remains. The three 450 hp fans for these levels operate as though they were in a true parallel installation even though they lie remotely from each other as can be seen in Figure 5. In Figure 5, the haulage level is only partly shown for illustration purposes. Each fan has its own fan drift originating from the main drift which has two air lock doors at about 91 metres (300 feet) apart.

Thus, the practice of installing fans underground tends to favor axial flow fans over centrifugals. The main reason for installing fans underground, rather than on surface, was because of the inconvenience that would be created by airlocks necessary in those operating shafts where the fans were installed. Another critical consideration is that MSHA allows underground installations of main fans in metal mines. The ventilation at San Manuel Mine is classified as a blowing system.

Operating axial flow fans on the major intake levels has its advantages. When multiple fans are required they are installed in parallel and remotely from each other in drifts connecting the extreme sides of the ore-body. They are matched easily by varying the blade pitch until essentially, the fans deliver exactly the same quantity and the same pressure and electrical power consumption. Air flow can be regulated from the fans themselves rather than devices installed in other parts of the ventilation system. One feature of fans operating to feed the same ore-body is that the resistance pressure of the system increases and forces each individual fan to work harder, as will be explained later.

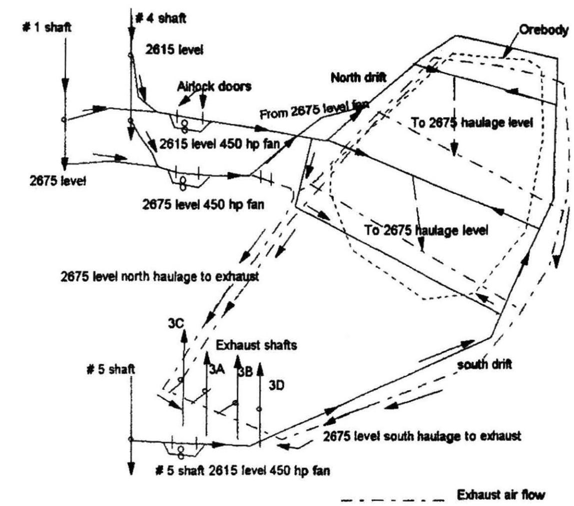

Figure 5. Illustration of fan installation at the 2615/2675 level (not to scale)

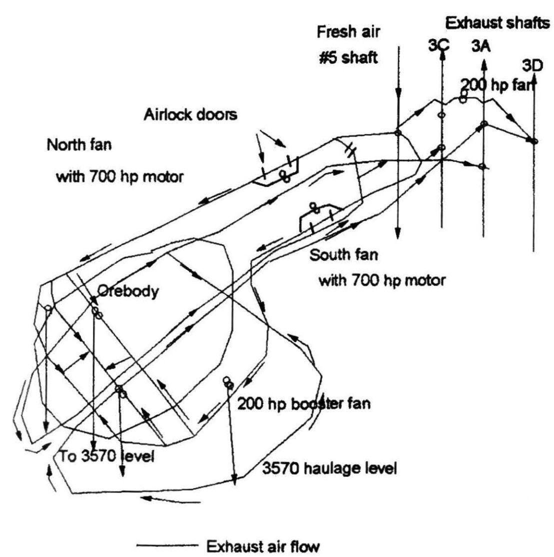

Figure 6. Illustration of fan installation and mining area on the 3440/3570 levels (not to scale).

Multiple fans in the same circuit

As mentioned earlier the operating point of a fan will vary depending on the other fans in the circuit. At San Manuel two production levels have multiple main fans which feed the same part of the ore-body. As can be seen in Figure 5 there are usually two main drifts leading to the same ore body. These drifts at San Manuel lie on the north and south respectively and are connected in the ore-body by a panel drift running from north to south. This means that the air streams from the main fans will meet and eventually flow into the grizzly drifts where production is in progress. From here the air is pulled by 20 or 30 hp production ventilation fans mounted on top, or below, the vent raise to downcast air to the haulage level and to the exhaust shafts.

On the new levels of the mine the intake level is the 3440 level. On this level fresh air is pulled from Number 5 shaft as shown in Figure 6. The north and south drifts have identical axial flow fans 1.8 metres (6 foot) in diameter which pull air from number 5 shaft. The air from both fans will flow as shown and the two air streams meet in the ore-body. These fans for practical purposes are in parallel even though they are located remotely from each other. The fans were selected to satisfy a design combined air flow of 218 m^3/s (460,000 cfm) at 3 kPa (12") mine static pressure with each fan moving 109 m^3/s (230,000 cfm). The south fan on the 3440 level was installed first. At that time the south fan delivered 109 m^3/s (230,000 cfm) into the mine at 3 kPa (12" w.g.) static pressure. About a year later the north fan was commissioned and as a result the system pressure increased from 3 to 4 kPa (12" to 16" w.g.) static pressure. The south fan was almost running at 100 % of electrical load on the 700 hp motor, and at the same time the north fan was at 45 % power consumption. Therefore the south fan blades were pitched down while the north fan blade angle was increased until the two fans delivered the same quantity at the same static pressure. Each fan was then delivering about 71 m^3/s (150,000 cfm) into the mine at 4 kPa (16" w.g.) static pressure and consuming about 85% of the installed motor horsepower.

As more panel drifts and ventilation raises were opened the mine pressure was gradually falling and at the same time the airflow quantity was increasing. Between 1996 and 1998, over a two year period the mine pressure reduced from 4 kPa (16" w.g.) to 3.5 kPa (14" w.g.) and at the same time the amount of air delivered to production and development areas increased from 71 m^3/s (150,000 cfm) to 94 m^3/s (200,000 cfm) per fan, i.e,. a total of 188 m^3/s (400,000 cfm) at 80% of installed motor power. Ventilation on this level and the one below it (3570 level) improved significantly. Production tonnage and develop-ment were also increasing at the same time.

One more pronounced feature of operating more than one main fan system such as the Lower Kalamazoo levels is that when one fan is turned off, the remaining fan increases its quantity. For example, as much as 127 m^3/s (269,000 cfm), up from 94 m^3/s (199,000 cfm), flows into the mine from one fan when the other fan is turned off. The mine pressure also decreases from 3.5 to 2.5 kPa (14" to 10") static pressure or less as shown in Figure 7. The combined effect of using two main fans in remote parallel locations and feeding the same ore-body by connecting drifts has the effect of adding resistance to the mine. It is as though the fans are "opposing each other." The solution in this case is to match the fans. One observation of the 3440 level main fans was that when the pressure was running high and they were at different operating points, the fans started experiencing aerodynamic stall which was quickly corrected to avoid damaging the fans. Pressure surges in the system do not help either when the situation is such that one or both fans start operating to the left of its curve. Surges in the system are easily introduced by open-ing and closing control doors in the mine.

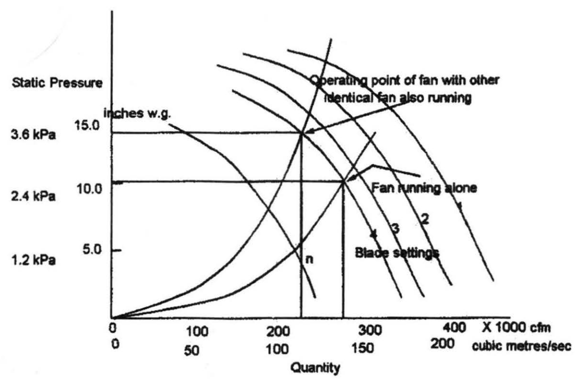

Figure 7. Axial flow fan curve showing the effect of one fan operating in a remote parallel installation with another identical fan and also the effect of one running with the other fan off.

Main ventilation system features

Once the practice was established of locating main fans underground the ventilation system had to be sustained and difficulties associated with this set up overcome. The advantages of operating fans underground have outweighed the disadvantages. The ore-body at San Manuel mine is well suited to have fans underground. Since it is a multi-level operation each system of levels have their own main fans and it is as though there are many mines within one mine, each with its own ventilation system. When ventilation of one of the major levels fail, the other levels are not affected. For example, if the fans at the 2615/2675 levels fail, the fans at the 3440 level continue operating as if nothing has happened, even though they exhaust in the same exhaust shafts and share Number 5 shaft for intake air. When the main fans at the 3440 level fail, they do not affect the upper levels. This is not true if the levels are connected by a raise or drift i.e. what happens at the 2675 will affect the 2615 level, and vice versa since both share the same ventilation path directly.

The upper levels, including the 2890 and 2950 levels, have some differences when compared to the 3440/3570 levels of the San Manuel mine. These differences cannot be ignored by the ventilation engineer because they demand special attention be paid to the ventilation system in the new levels. For a long time the 3440/3570 levels were only connected directly to one of the smaller rectangular exhaust shafts. Even though 3D shaft reached the level it did not receive exhaust air directly from the new levels. This is not the case with the upper levels. The major drifts in the lower levels were developed by a Tunnel Boring Machine (TBM) and are larger than the traditional drifts, but this feature was nullified by the fact that bottle necks existed in airways leading to the exhaust shaft. This meant that the main fans operated with higher than the design mine pressure. Conveyer belts are installed on the panel drifts on the haulage level which increases air way resistance. The ventilation raises that downcast air from the production level to the haulage level are 40 m (130 ft) deep compared to 18.3 m (60 ft) on the upper levels and have somewhat smaller hydraulic diameter, again increasing the diameter.

After many critical assessments which included computer modeling, it was decided to develop an exhaust drift for the new levels dedicated to ventilation only that would tie into 3C shaft, one of the larger circular shafts. This project is underway and almost complete at this time. The projected mine plans require a production level of 55,000 to 60,000 tons per day from the new levels when the other levels are depleted. This would require at least 260 m^3/s (550,000 cfm) to satisfy production, development and maintenance shops. The main fans would need to operate at less than 2.7 kPa (11" w.g.) in that situation, despite adding exhaust routes and larger motors, the op-erating pressure would still be too high. This will not be desirable. A solution being tried is to use "a push and pull" ventilation system where the existing fans remain where they are while exhaust fans are installed in the exhaust drifts leading to the shafts.

Computer network modeling of this system shows that this would work. In this case, the intake and exhaust fans would now share the system pressure therefore allowing more air to be introduced in the system. Adding more exhaust drifts is hardly an option at this stage because of the present infrastructure of the mine. It would be a logistic problem but it could be done. Installing exhaust fans is more convenient option.

As seen in Figure 3, not all main fans are large, some levels have direct mount axial flow fans of 50 to 200 hp in size. These fans are used to ventilate small levels as well as pump stations and ore spill levels. They can move between 15 to 50 m^3/s (30,000 to 100,000 cfm). The oldest part of the mine, with in-situ mining, uses 200 - 250 hp fans. In some cases where there are maintenance shops 40, 50 and 60 hp axial fans operating in parallel flow are used to pull air from the main intake shaft into the shop, providing the required airflow.

Axial flow fans for production and development ventilation

As shown in the Plan View of a typical production area of a block caving system at San Manuel Mine (Figure 2), there is an access drift between the two major panel drifts. Every three or four lines a ventilation raise is developed just off the access drift. This ventilation raise joins the haulage level drift down below. The cross sectional area of the raise is 1.5 to 1.8 m^2 (16 to 20 ft^2) and can either be square or round in shape. Air from the panel drifts flows through the grizzly lines to the access drift and downcast a vent raise. Grizzly line airflow quantity requirements range from 2 to 3 m^3/s (4,000 to 6000 cfm). In the older levels the vent raise is 18 m (60 feet) deep and 20 hp fans are installed at the bottom of the raise on the haulage level. Typically the fans were axial flow rotating at 1760 RPM and pulling 12 m^3/s (25,000 cfm) through the grizzly lines above, on the production level.

In the newer part of the mine, i.e. the 3440/3570 levels, the fans are installed on top of the vent raise as shown in Figure 2 and are made to operate with 30 to 40 hp motors to move up to 17 m^3/s (35,000 cfm) to the haulage level 40 m (130 feet) below. The vent raise fans can overcome any pressure between 0.12 to 1.0 kPa (0.5 to 4" w.g.) static pressure. These small fans assist the main ventilation fans by directing the airflow where it is needed and also adding some pressure energy in the process.

Development ventilation is divided into two areas at San Manuel Mine. The first is primary development in which major panel drifts are driven on both the production and haulage levels. In primary development large diesel engines of up to 200 hp are used for excavation. These development headings are supplied with up to 14 m^3/s (30,000 cfm) airflow depending on the diesel equipment in use. The primary headings can be up to 305m (1,000 ft) long. The fans used for primary development are axial flow and range from 60 to 100 hp capacity. Ventilation ducting of 914 mm (36") in diameter is used with these fans. Strict monitoring is practiced in order make sure adequate ventilation is maintained in blind excavations.

Once major panels are driven, secondary development is then responsible for driving the grizzly drifts, concrete support, and ore undercut raises for the eventual production of ore. The grizzly transfer raises are developed using raiseboring machines. The secondary development excavation headings for grizzly lines uses smaller diesel equipment which can be up to 100 hp. The size of the axial flow fans used in secondary development range from 20 to 40 hp delivering up to 8 m^3/s (16,000 cfm) airflow. The secondary headings are 46 to 92 m (150 to 300 ft) long. The size of the ventilation ducting is usually 609 and 762 mm (24" and 30") in diameter. The exhaust of the air from the heading will discharge in the main panel where it flows to the main exhaust system. It is common practice to adjust the blades of the small fans as well to suit the ventilation application required.

It is common practice at San Manuel Mine to employ axial flow type booster fans to provide the primary ventilation air needed to support auxiliary fans in certain areas of the mine. Without these booster fans moving up to 50 m^3/s (100,000 cfm) it would almost be impossible to satisfy ventilation requirements of the whole mine. On the 3440 level there are currently two booster fans supplying air to primary development headings. One of the booster fans (a 150 hp) is used to clear diesel fumes from a multiple faced development heading. The other booster fan is a 200 hp fan with adjustable blade pitch. All small and booster fans are axial flow fans with direct mounted motors.

CONCLUDING REMARKS

At San Manuel production is seven days a week and three shifts a day, and therefore once the airflow is set for the mining activity it does not need to be changed for quite sometime. Once mining activities demand a change in the ventilation air supply, fan blade angles are adjusted to supply the necessary air flow quantity and pressure. Therefore variable speed drives (VFDs) are not justified for this type of mine. The main fans at San Manuel have not been operated in series to generate more pressure because at the ventilation design stage, the fans are selected to generate enough pressure and quantity at all stages of the mine development and production. The motors driving the fans can be upgraded if it becomes critical to satisfy the new quantity and pressure at a higher blade pitch. The fan will arrive from the manufacturer capable of being operated with the maximum motor horsepower the fan can handle mechanically. For example, the manufacturer will give the customer the freedom to choose a motor of his choice and recommending that the fan can take a maximum of 1200 hp. Quite often much less horsepower is applied.

The major problem with axial flow fans is that of noise. Fortunately at San Manuel fans are located underground in remote areas far from the mining activity. The other problem with older fans is that of vibration, but if they are all well maintained this can be kept under control.

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